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THE OHIO STATE UNIVERSITY

RESEARCH FOUNDATION

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FINAL REPORT

SUPERSONIC BURNING AND COMBUSTION

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Report No. 3

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By

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On SUPERSONIC BURNING AND COMBUSTION

For the period 1 February 1966 - 31 March 1967

Submitted by R. Edse

Department of Aeronautical and Astronautical Engineering

Date November 9, 1967

SUPERSONIC BURNING AND COMBUSTION

Three different phases of research were carried out during the period covered by this report: (1) The transient pressures in the induction region of hydrogen - oxygen detonations were measured, (2) the induction distance and wave speeds of detonations in liquid fuel sprays were determined, and (3) efforts were made to stabilize a combustion wave in a supersonic stream of premixed hydrogen - air mixtures.

Transient Pressure Measurements in the Induction Region of Hydrogen-Oxygen Detonations

The pressures occurring in the induction region of various hydrogen-oxygen mixtures were measured with piezoelectric quartz transducers. The phenomenon of onset of detonation could, therefore, be analyzed from a completely different set of experimental data than has previously been employed. The effect of the ignition section geometry on the formation of the detonation wave was also examined.

The detonation tube employed had an inside diameter of 79 mm and was five meters long. Over this length, ionization probe measurements were made of the velocity of the reaction zone. These data were correlated with those obtained by the pressure transducers.

The mixtures were ignited with a nichrome glow wire 1/8-inch long and 0.025-inch in diameter. The wire was heated electrically to the lowest temperature necessary to ignite the mixture. This procedure was followed in order to minimize the effects of energy added to the mixture by sources other than the reacting gas itself.

Detonation induction phenomena were examined in the following mixtures:

(a) $75\ H_2 + 25\ O_2$
(b) $66.7\ H_2 + 33.3\ O_2$
(c) $55\ H_2 + 45\ O_2$.

From ionization probe data, the obtained pressure profiles, and previously obtained schlieren data,[1] the following analysis was derived for the induction process in a constant area duct containing a stoichiometric mixture of hydrogen and oxygen, initially at atmospheric temperature, and ignited by a hot wire ignitor centered in the flat end wall of the tube.

When the temperature of the hot wire reaches a value of approximately $700^{o}K$, ignition occurs in the immediate vicinity of the hot wire, and the resulting flame propagates in a hemispheric laminar fashion to the tube wall and downstream into the static mixture. When the burning reaches

the wall, the hemispheric front collapses into a convex, laminar, one-dimensional flame front.[1] During this time, the flame is accelerating slightly, thus emitting a "compression fan" which propagates into the unburned mixture and raises the temperature of the gas.

After the flame front has passed over the gas the combustion products are set into motion and follow the wave. Because of this motion and the effect of cooling of the burned gas by the cold walls of the tube an expansion wave is formed at the ignitor end wall of the tube which propagates sonically with respect to the burned products. Thus, the expansion wave overtakes the flame front, and passes through it. The interaction of the expansion wave with the flame front and the reacting boundary layer near the flame front causes the flame front to become unstable and turbulent.[1] This in turn ends the strengthening of the compression fan which was produced by the accelerating flame front, and leads to the formation of a narrow shock zone, the precursor shock (Fig. 1).

The foregoing initial processes appear to be very reproducible. In the tube employed, the precursor shock was always formed at approximately 40 cm from the ignitor, and it traveled at approximately Mach 1.5, producing a pressure behind it of approximately 2.5 atm for stoichiometric and slightly leaner mixtures. For the richer mixtures, the precursor shock was slightly weaker and was formed at a distance of 55 m from the ignitor.

When the precursor shock is formed, it travels well ahead of the turbulent flame front. The burning, because of its turbulent nature, emits several finite compression fans which interact and coalesce and form a series of shock waves immediately ahead of the flame front. This process raises the temperature of the unburned gas until a localized explosion takes place between the turbulent flame front and the shock waves.[2] This "explosion within an explosion" causes a pressure overshoot (point of onset of detonation; point of onset of retonation). In this overshoot region, pressures of 60 atm are common in stoichiometric and slightly lean mixtures, but in mixtures of 75% H_2 + 25% O_2 by volume, the overshoot pressure in a normal geometry tube rarely exceeds 30 atm. This is interesting in that the stable detonation pressure measured in all three examined mixtures is approximately the same.

Beginning at the point of the pressure overshoot, two different strong shocks are seen to propagate in opposite directions from the point of highest pressure. The shock propagating rearward toward the ignitor is the retonation wave. In the opposite direction, a strong shock produces an overdriven detonation (shock strength preceding flame front exceeds that predicted by a Chapman-Jouguet analysis) which propagates with diminishing strength until it assumes the Chapman-Jouguet condition (Fig. 2).

The previously mentioned precursor shock, after its formation, travels well ahead of the rest of the induction process. This shock induces no reactions in its wake and apparently has only the effect of preheating

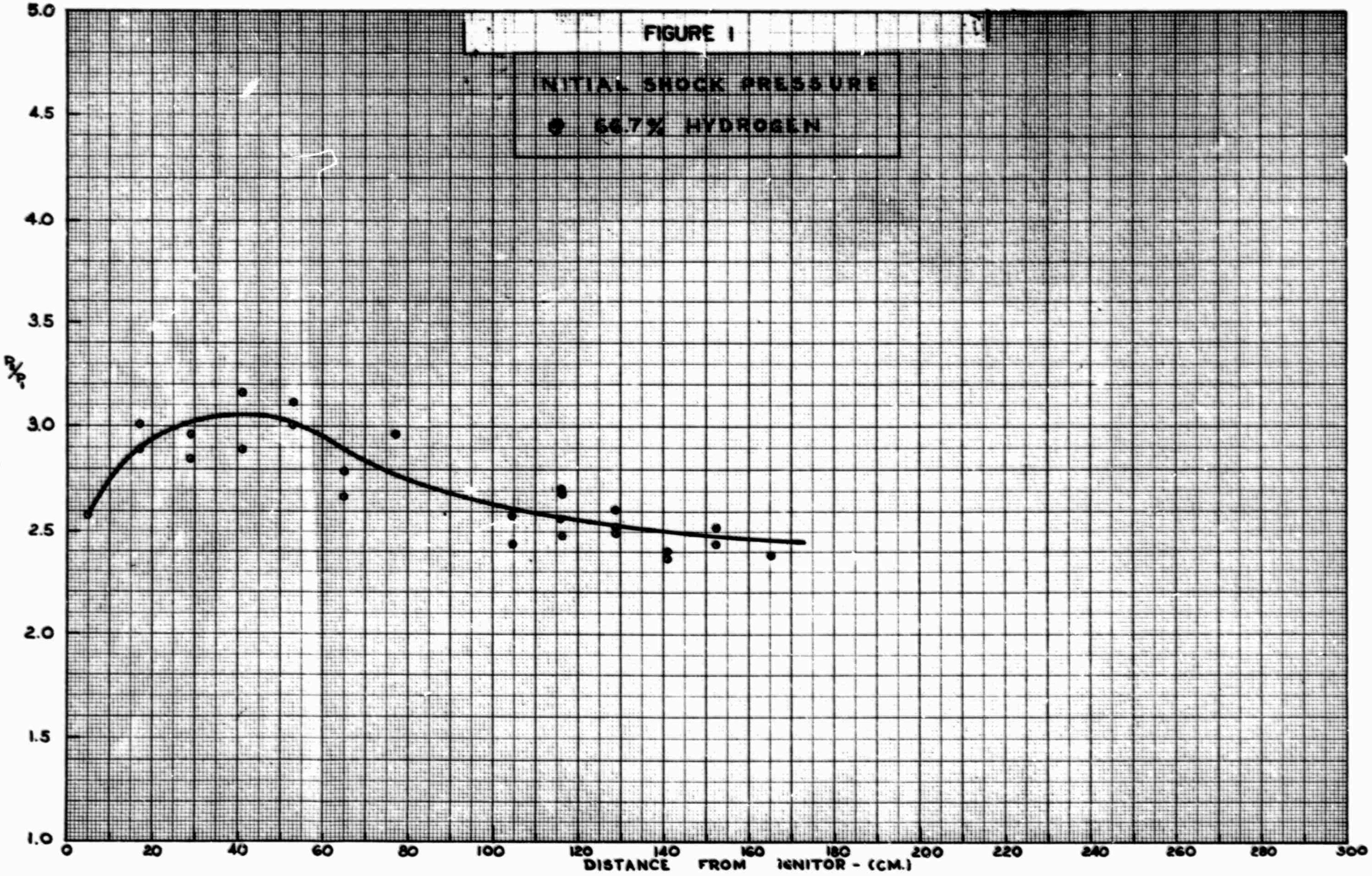
FIGURE 1
INITIAL SHOCK PRESSURE
66.7% HYDROGEN
P_2/P_1
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
DISTANCE FROM IGNITOR - (CM.)

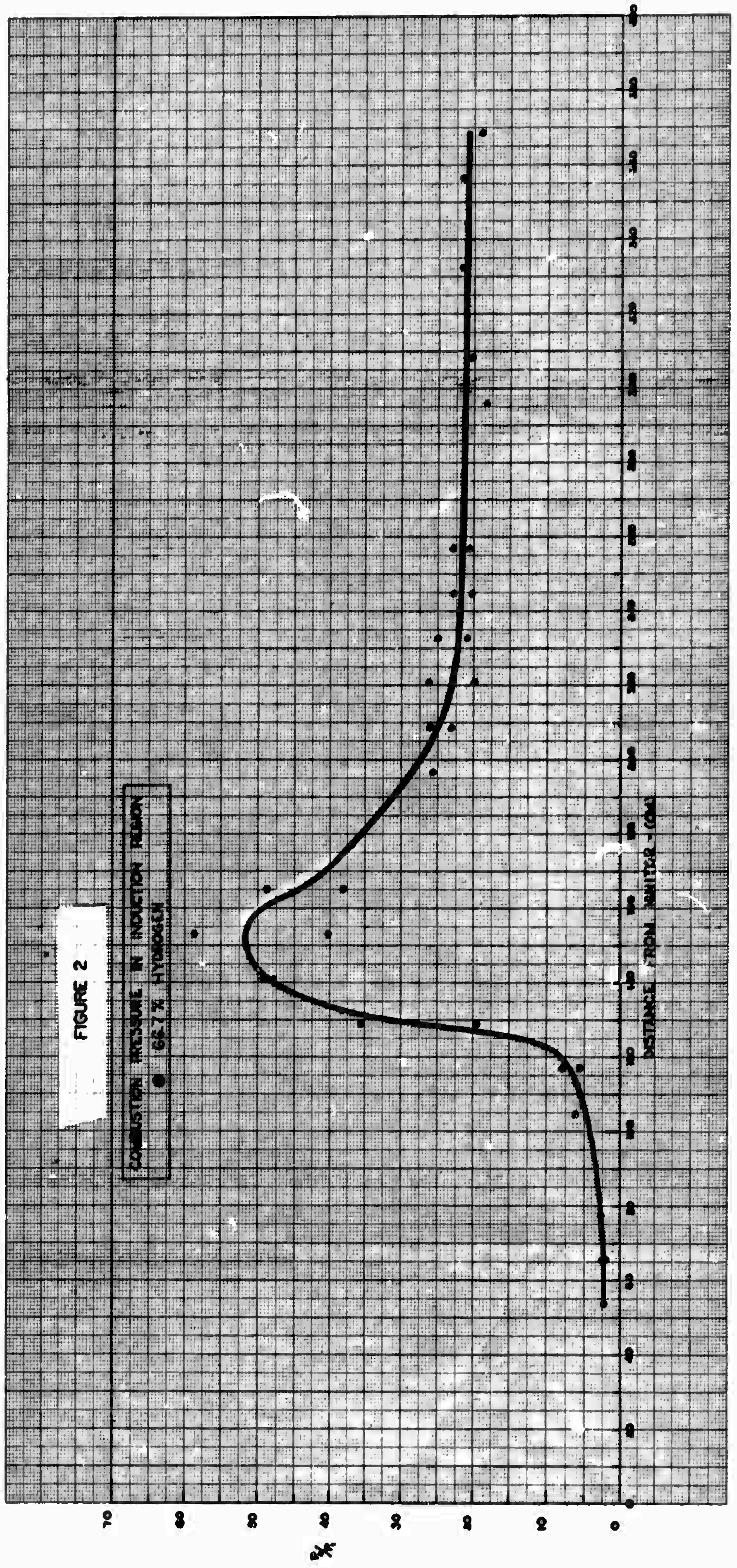
FIGURE 2
COMBUSTION PRESSURE IN INDUCTION REGION
66.7% HYDROGEN
DISTANCE FROM IGNITER - (CM)

the unburned gas slightly and setting it into a slight turbulent motion due to the slight shocking action.

In the stoichiometric and leaner mixtures, this precursor shock was overtaken by the overdriven detonation soon after the point of onset of detonation. However, in the richer mixture examined, the precursor was considerably further downstream of the flame front when the onset of detonation occurred. Therefore, it was not overtaken until after a stable configuration had been reached by the detonation process in its wake. The pressure in the gas behind the detonation wave decreased slightly after the wave had passed over the precursor shock. This reduction in pressure is in agreement with theory.

The introduction of a conical ignition section causes definite changes in the induction properties. Although the process remains qualitatively the same, the pressures measured throughout the induction region vary significantly from those measured when ignition takes place in a constant area tube.

The introduction of a 15-degree half angle cone into the apparatus expands the ignition region diameter from 12.7 mm at the ignitor to 79 mm over a distance of 124 mm. This conical section causes the precursor shock to be weakened, and formed much sooner than in a constant area duct. It appears that the cone expands the compression fan moving ahead of the laminar flame when the flame initially accelerates, and the expansion wave initiating at the ignitor wall seems to form sooner, the result being that the shock formed is weaker than in the unexpanded case. Another result of the insertion of this conical section is a significant reduction of the strength of the pressure overshoot at the point of onset of detonation. This reduction is possibly caused by the weakened precursor shock, but an analytical correlation is not immediately seen. In the stoichiometric and slightly lean mixtures, the overshoot is reduced by approximately 1/3, as the overshoot is now rarely over 40 atm in both these mixtures.

A further change was made in the ignition section configuration by removing the cone, and recessing the hot wire ignitor in a 1-inch deep, 1/2-inch diameter hole in the center of the flat end wall of the tube. The first pressure measurements were taken 5 cm after the flame had entered the tube from the recessed ignitor. At this point, it is observed that the precursor shock is much weaker than that obtained in the constant area duct. The shock is followed very closely by an expansion wave which in turn is closely followed by a compression fan which coalesces into a second precursor shock a very short distance further down the tube. This second precursor shock soon overtakes the first one.

Upon comparison of pressure-time traces with and without the recessed ignitor, it was noticed that at a distance of 30 cm from the end wall, there are significant differences for the two cases. When the ignitor is not recessed, the precursor shock is not yet formed at this

point, since the compression fan is still in the process of coalescing. A noticeable expansion fan immediately follows this precursor. With the ignitor recessed, the precursor at this point is fully developed, and only a very slight expansion is noticeable in its wake. Because of the difference in the expansions behind the precursor shocks in the two cases, the point of onset of detonation with the ignitor recessed takes place 40 cm sooner than with the ignitor unrecessed. It appears that this principle could be applied to a further recession of the ignitor, resulting in a further decrease in the distance between the ignitor and the point of onset of detonation.

Detonation Phenomena in Mixtures of RP-1 and O_2

In this phase of the project, detonations in mixtures of liquid RP-1 and gaseous oxygen have been studied with strip film techniques by detonating the mixture in 8-foot-long glass tubes of 30 mm and 48 mm inside diameter. In this way, both induction distance and detonation velocity could be determined from the film. The mixture ratio (mass of oxygen/mass of RP-1) was varied from 4.8 to 0.5, with emphasis on the stoichiometric region (approximately 3.4).

When the mixture was unheated, experiments made in the 48-mm tubes did not produce reproducible data. The burning was oscillatory and unsteady for the most part. The values for the detonation velocity were 70% of the theoretical values calculated with a NASA program of Gordon and Zeleznik.[3,4] It was felt that this discrepancy between theory and experiment was caused by incomplete burning of the liquid droplets in the front, as shown in the "afterburning" phenomena seen in all experiments.

An attempt was made to increase the amount of RP-1 vapor in the mixture by preheating the RP-1 to 100, 125, and 150°C, and introducing the heated RP-1 into both heated and unheated oxygen. When the oxygen was unheated, it was found that the mixture formed a fog due to RP-1 vapor condensing.

Heating the RP-1 to 100°C and introducing it into oxygen at room temperature produced mixtures in which the detonation velocity was found to vary from 1500 to 1750 m/sec. On increasing the RP-1 temperature to 125°C, the detonation velocities varied from 1700 to 1850 m/sec over the same range of mixtures examined. Nearly identical velocities were obtained when the RP-1 temperature was futher increased to 150°C. It was observed that tube diameter and type of ignitor appeared to have no effect on the final detonation velocities.

Finally, both the RP-1 and oxygen were heated to 92°C. In this mixture, two modes of detonation, each having a steady speed, were observed. One mode was oscillatory, with a velocity approximately 100 m/sec below the velocity of the nonoscillatory mode in the same mixture.

The one-dimensional, nonoscillatory detonations in this heated mixture had speeds ranging from 1600 to 1700 m/sec over the examined range of mixture ratios.

Although further work is necessary to elucidate the mechanism of detonations in liquid fuel spray-oxygen mixtures, it has been decided to terminate the study at this point because of more important studies in the field of supersonic combustion.

Attempts to Establish Burning Behind an Oblique Shock Wave in a Premixed Supersonic Flow of Hydrogen-Air Mixture

Various aerodynamic bodies were placed in a supersonic flow of premixed hydrogen - air mixtures in order to examine the burning properties which are of practical importance in the operation of supersonic ramjets. With the various bodies used and several modes of ignition, burning occurred only in the subsonic region while no steady flame could be established behind the oblique shock waves.

The Mach number of the supersonic flow ranged from 2.6 to 2.9 with a stagnation temperature of only 300°K. Attempts to ignite the supersonic flow by external shock and detonation waves appeared to be possible. However, no conclusions can be drawn from the results obtained during this contract period. Further work on this phase of the research is in progress.

Publications

Report on RP-1 to be submitted.

Graduate Students

Mr. Lloyd R. Lawrence, Jr.	Ph.D.
James E. Orkins	Received M.S.

Loren Bollinger was principal investigator and supervised work from 1 February, 1966 until his death in May, 1966.

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Investigator R. Edse Date 20 NOV 67

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13. ABSTRACT

A final report is given on three phases of research: the transient pressures in the induction region of hydrogen-oxygen detonation waves, detonation waves in mixtures of liquid RP-1 and gaseous oxygen, and stationary supersonic combustion waves.

The measurements of the transient pressures during the formation of hydrogen-oxygen detonation waves reveal a large "pressure overshoot" at the point of onset of detonation. This overshoot may be two to three times as large as the pressure at the Chapman-Jouguet condition. The magnitude of the overshoot depends on the geometry of the ignitor section.

Detonation waves in mixtures of oxygen and RP-1 were sometimes smooth and sometimes oscillatory. It was not possible to obtain definite values for the induction distances.

Experiments to establish supersonic combustion behind oblique shock waves in hydrogen-air flows did not yield conclusive results.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Chapman-Jouguet						
Detonation						
Expansion wave						
Flame						
Hydrogen						
Hydrogen-Air						
Ignition						
Induction-Distance						
Liquid fuel sprays						
Oblique shock						
Oxygen						
Piezo-electric transducer						
Precursor shock						
Premixed supersonic flow						
Pressure measurements						
Spinning detonation						
Supersonic burning						
Supersonic combustion						
Variable geometry						

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